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FERMILAB-Conf-97/291-E
CDF

# Branching Fractions and Polarization of CP Eigenstates: CDF and Cleo

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August 1997

Published Proceedings of the *2nd International Conference on B Physics and CP Violation (BCONF97)*, Honolulu, Hawaii, March 24-28, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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# BRANCHING FRACTIONS AND POLARIZATION OF *CP* EIGENSTATES: CDF AND CLEO

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Recent experimental results on branching ratios and polarization in $B^0 \to J/\psi K^{(*)}$ decays including the first measurements of three independent amplitudes that describe $B \to J/\psi K^*$ decays are reviewed and compared to theoretical preditions. Results of the CLEO search for $B^0 \to D^{(*)+} D^{(*)-}$ are summarized.

## 1 Introduction

Much of the interest in $B$ physics is focussed on the potential for observation of *CP* violation in $B$ decays. The first constraints on the CKM matrix arising from measurements of *CP*-violating asymmetries will likely come from measurements of the angle $\beta$ of the CKM unitarity triangle. Measurement of the branching ratios of *CP* eigenstate decay modes is important for determination of the sensitivity to *CP* violation of experiments now under construction. Two decay modes of experimental interest are[a] $B^0 \to \psi K^{(*)}$ and $B^0 \to D^{(*)+} D^{(*)-}$. Such measurements are difficult because of the need to tag the initial flavor of the $B$ meson and because the product branching ratios in experimentally observable decay modes are small. The decay $B^0 \to \psi K^0_S$ is manifestly *CP*-even. But because it is a vector-vector decay and contains $S$-, $P$-, and $D$-wave contributions, to use the decay $B^0 \to \psi K^{*0}$, $K^{*0} \to K^0_S \pi^0$ for measurement of *CP*-violating asymmetries, it is necessary to determine the *CP*-even and *CP*-odd fractions. Also, a determination of the polarization fractions for $B^0_s \to J/\psi\, \phi$ decays can aid in determining the difference between the even and odd eigenstates in $B_s$ decays.[1] Finally, phenomenological models[2−5] predict simultaneously the widths of $B \to \psi K$ and $B \to \psi K^*$ and the polarization of $B \to \psi K^*$ decays, and comparison to experimental results can test the validity of the factorization ansatz in these decay modes.

CDF at the Fermilab Tevatron and CLEO II at CESR provide quite complementary environments for $B$ physics. At CDF boosted $B$ mesons created in $p\overline{p}$ interactions are identified with a dimuon trigger. Light-quark backgrounds are rejected by requiring reconstructed $B$ candidates to have decay vertices displaced from the beam line, and $B$ backgrounds, with fragmentation-energy

[a] $\psi$ refers in general to $J/\psi$ and $\psi(2S)$ mesons; $K^*$ refers to the $K^*(892)$. Where a particle decay mode is specified, the charge-conjugate mode is implied.

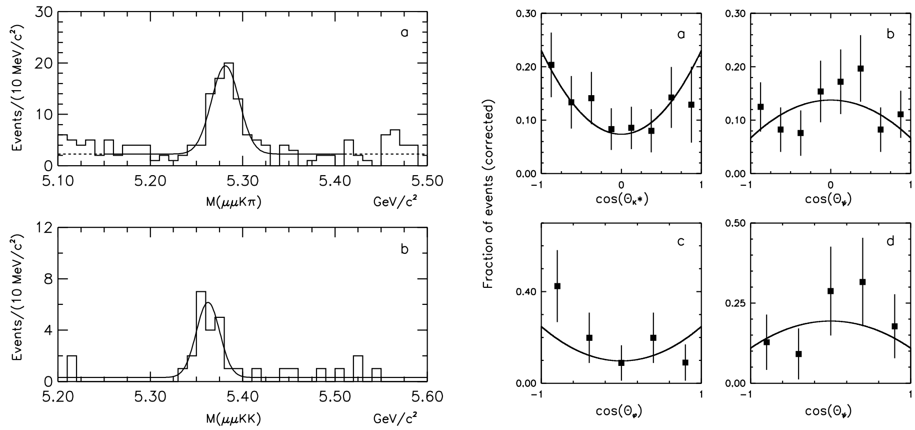


Figure 1: CDF mass and decay-angle distributions for $B^0 \to J/\psi\, K^{*0}$ (upper) and $B^0_s \to J/\psi\, \phi$ (lower). From left to right: Histogram of reconstructed masses with curve showing the fit to a Gaussian line shape and a uniform background; the strange vector-meson decay angle ($\cos\theta_{K^*}$ or $\cos\theta_\phi$) with the polarization fit result; and the $J/\psi$ decay angle ($\cos\theta_\psi$) with the fit result.

cuts. CLEO reconstructs $B$ mesons created at threshold in $e^+e^- \to \Upsilon(4S)$ interactions and uses an open trigger for hadronic events. Non-$B$ backgrounds are rejected by event-shape requirements, while $B$ backgrounds are rejected by requiring the candidate to have an energy consistent with the beam energy.

## 2 CDF: Polarization and Branching Ratios

To reconstruct $B$ candidates, CDF first searches for $J/\psi \to \mu^+\mu^-$ or $\psi(2S) \to \mu^+\mu^-$ candidates in the data sample selected by the dimuon trigger path. The transverse momentum $p_T$ of each muon is required to be greater than $2\,\mathrm{GeV}/c$. The mass of the dimuon candidate is reconstructed subject to the constraint that the two muons originate from a common decay vertex. $J/\psi$ or $\psi(2S)$ candidates are combined with additional charged-particle tracks or neutral-V candidates, and the $B$ candidate mass is formed subject to the constraints that all tracks (or vees) come from a common decay point, the mass of a $J/\psi$, $\psi(2S)$ or $K^0_S$ candidate corresponds to the known value,[6] and the momentum of the $B$ candidate is collinear with the displacement of the decay vertex from the primary $\overline{p}p$ interaction vertex. The particle mass associated with each track in the reconstruction is assigned based on the decay-mode hypothesis. If a $K^{*0} \to K^+\pi^-$ candidate satisfies either set of mass assignments, the assignment with mass closest to the $K^*$ pole is chosen, and the mass of a

Table 1: Results for $B \to J/\psi K^{(*)}$ Branching Ratios

| | CDF | CLEO |
|---|---|---|
| $\mathcal{B}(B^0 \to J/\psi\, K^0) \times 10^{-3}$ | $1.14 \pm 0.27 \pm 0.09$ | $0.85^{+0.14}_{-0.12} \pm 0.06$ |
| $\mathcal{B}(B^0 \to J/\psi\, K^{*0}) \times 10^{-3}$ | $1.39 \pm 0.32 \pm 0.11$ | $1.32 \pm 0.17 \pm 0.17$ |
| $\mathcal{B}(B^+ \to J/\psi\, K^+) \times 10^{-3}$ | $0.82 \pm 0.18 \pm 0.07$ | $1.02 \pm 0.08 \pm 0.07$ |
| $\mathcal{B}(B^+ \to J/\psi\, K^{*+}) \times 10^{-3}$ | $1.73 \pm 0.55 \pm 0.15$ | $1.41 \pm 0.23 \pm 0.24$ |
| $\frac{\mathcal{B}(B \to J/\psi\, K^*)}{\mathcal{B}(B \to J/\psi\, K)}$ | $1.32 \pm 0.23 \pm 0.16$ | $1.45 \pm 0.20 \pm 0.17$ |

$K^*$ ($\phi$) candidate is required to be within $80\,\mathrm{MeV}/c^2$ ($10\,\mathrm{MeV}/c^2$) of the pole mass.

### *2.1 Polarization*

CDF has measured the polarization of $B^0 \to J/\psi\, K^*$ and $B_s^0 \to J/\psi\, \phi$ decays in the $20\,\mathrm{pb}^{-1}$ Run 1A data sample.[7] A decay of a pseudoscalar to two vectors can be described in terms of three complex amplitudes. If the partial width or branching fraction of the mode is used as an overall normalization, the relative contributions of the different angular momentum states can be described in terms of an orthogonal basis. In the helicity basis, the three normalized amplitudes $H_+$, $H_-$ and $H_0$ describe the probabilities for the $\psi$ and $K^*$ to have helicities $+1$, $-1$ or 0 and can be represented by two real numbers and two phases. The longitudinal fraction is $\Gamma_L/\Gamma = |H_0|^2$.

For $B$ candidates within $30\,\mathrm{MeV}/c^2$ of the known mass,[6] the polarization is fit using a likelihood function that includes the decay distribution, the acceptance determined in Monte Carlo simulations, an unpolarized background distribution, and a signal-to-background ratio determined from the reconstructed mass. The shape of the background polarization distribution is checked in events from the $B$-mass sidebands. The residual $K\pi$ misassignment gives a $0.041 \pm 0.026$ shift in $\Gamma_L/\Gamma$, independent of its value. CDF finds:

$$\begin{aligned} \Gamma_L/\Gamma\,(B^0 \to J/\psi\, K^{*0}) &= 0.65 \pm 0.10 \pm 0.04 \\ \Gamma_L/\Gamma\,(B_s^0 \to J/\psi\, \phi) &= 0.56^{+0.20}_{-0.21}{}^{+0.02}_{-0.04}. \end{aligned}$$

In addition to the misassignment error, systematic uncertainties are derived by varying the $B$-meson $p_T$ spectrum and background polarization, by allowing for a non-resonant $K\pi$ component, and by varying the trigger model within measured uncertainties. The fit results are shown in Figure 1.

### *2.2* $B \to J/\psi\, K^{(*)}$ *Branching Ratios*

CDF also has measured the relative branching ratios for $B \to J/\psi\, K^{(*)}$ decay modes in the Run 1A sample,[8] searching for $K^+$, $K^0_S$ $K^{*+} \to K^0_S \pi^+$, and $K^{*0} \to K^+\pi^-$ candidates in association with each $J/\psi$. A $B$ candidate is required to have a displacement forward of the beamline ($c\tau > 0$) and $p_T > 6\,\mathrm{GeV}/c$. The $B$ yield in each decay mode is determined with a binned likelihood fit to the candidate mass distribution with a linear background function and a Gaussian line shape. Dividing the yields by the integrated luminosity and efficiency for each channel gives $\sigma \cdot \mathcal{B}$, the product of production cross section and branching ratio. Because the $B$ production cross section is not well determined from external measurements, it is not possible to find independently absolute branching ratios. However, forming ratios of branching ratios

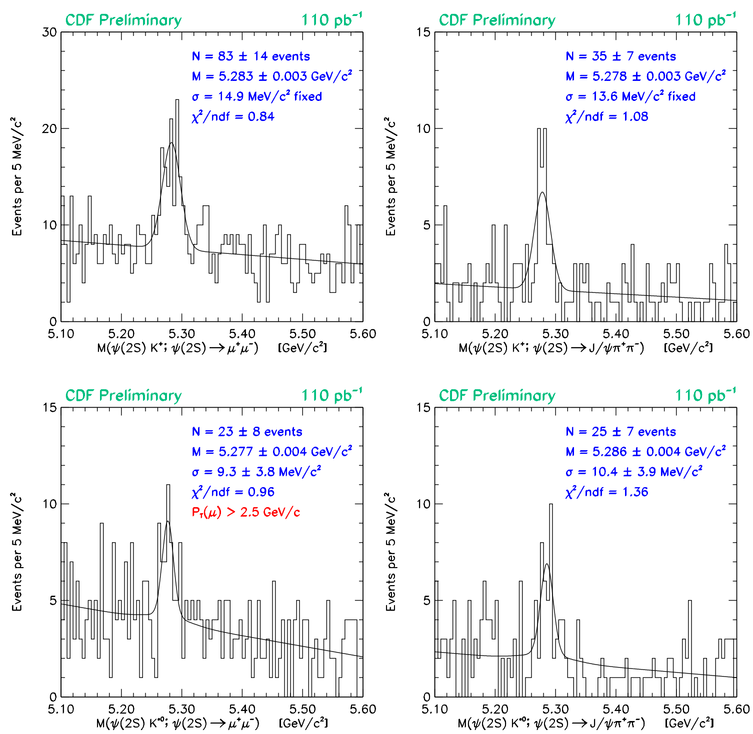


Figure 2: Mass distributions for $\psi(2S)\,K$ modes. The curve shows the result of the fit described in the text. Upper plots are $B^+ \to \psi(2S)\,K^+$, and the lower are $B^0 \to \psi(2S)\,K^{*0}$. For each, both the $\psi(2S) \to \mu^+\mu^-$ (left) and the $\psi(2S) \to J/\psi\,\pi^+\pi^-$ (right) modes are shown.

significantly reduces systematic uncertainties due to acceptance and due to trigger and tracking efficiencies. These ratios can be combined with the world average branching ratios[6] to construct a weighted average branching ratio in each mode, subject to the assumption that, as a result of isospin symmetry, $B^+$ and $B^0$ mesons are produced in equal numbers. The derived branching ratios and the vector-to-pseudoscalar decay ratio are listed in Table 1.

### *2.3 $B \rightarrow \psi(2S)\, K^{(*)}$ Branching Ratios*

Using a 110 pb$^{-1}$ data sample, CDF has measured branching ratios for $B$ decays including a $\psi(2S)$ normalized to similar $J/\psi$ decay modes so that efficiency and production uncertainties cancel. Both the $\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$ and $\psi(2S) \rightarrow \mu^+\mu^-$ decay modes have been used. The proper decay length $c\tau$ of the $B$ candidate is required to be greater than $100\,\mu$m, and the $B$ candidate is required to be well-isolated. Except for the additional mass requirement in the $\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$ decay, the same cuts are used for $J/\psi$ and a $\psi(2S)$decay modes. After weighting by the $J/\psi$ and $\psi(2S)$ branching ratios and relative reconstruction and trigger efficiencies, the measured ratios are:

$$R \equiv \frac{\mathcal{B}(B^+ \rightarrow \psi(2S) K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)} = 0.67 \pm 0.09 \pm 0.10$$
$$R^* \equiv \frac{\mathcal{B}(B^+ \rightarrow \psi(2S) K^{*0})}{\mathcal{B}(B^+ \rightarrow J/\psi K^{*0})} = 0.57 \pm 0.13 \pm 0.07$$

As a test of the factorization hypothesis, these results can be compared to theoretical predictions[9] of $R = 0.59 \pm 0.07$ and $0.25 \leq R^* \leq 0.67$.

## 3 CLEO: The Complete Angular Analysis

The branching ratio and , $_L$/, form an incomplete description of the decay for $B \rightarrow J/\psi\, K^*$. Furthermore, in the familiar helicity basis, the even and odd parity components of $H_+$ and $H_-$ are not eigenvalues of the decomposition. However, in the transversity basis,[10] it is possible to project out the *CP*-even *S*- and *D*-wave and the *CP*-odd *P*-wave contributions:

$$A_0 = -\sqrt{\tfrac{1}{3}}S + \sqrt{\tfrac{2}{3}}D \qquad A_\perp = P \qquad A_\parallel = \sqrt{\tfrac{2}{3}}S + \sqrt{\tfrac{1}{3}}D.$$

These amplitudes can be related to the helicity amplitudes by $H_\pm = (A_\parallel \pm A_\perp)/\sqrt{2}$ and $H_0 = -A_0$. CLEO fits the complete angular distributions in $J/\psi\, K^*$ decays[11] parameterized in terms of the branching ratio, two fractional amplitudes, and two relative phases with $A_0$ chosen to be real.

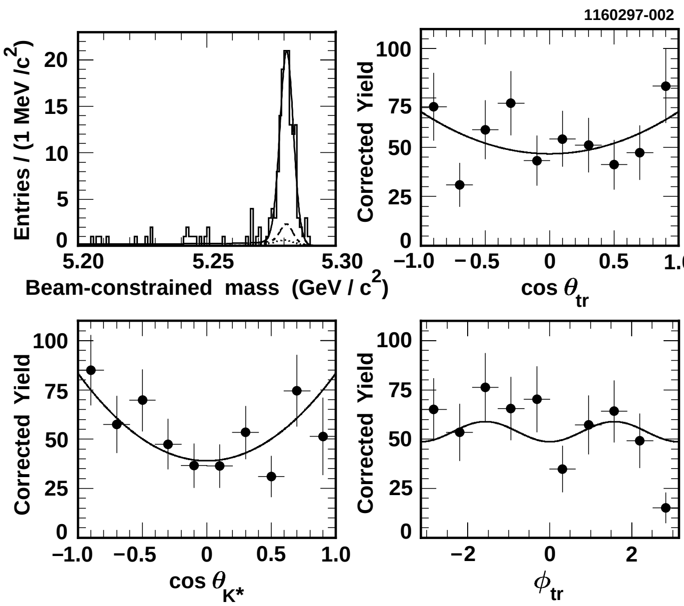


Figure 3: The upper left plot shows the mass distribution for $J/\psi K^{*+}$ and $J/\psi K^{*0}$ events seen by CLEO. The solid line is the fit result. The dashed line shows the sum of all backgounds, and the dotted, the contribution of feed-across only. The remaining three plots show the distributions of the angular variables in the transversity basis. The points are background-subtracted data corrected for efficiency, and the curve indicates the fit result.

In a $3.1\,\mathrm{fb}^{-1}$ data sample corresponding to $3.4\times10^6$ $B\overline{B}$ events, $B\rightarrow J/\psi\, K^{(*)}$ candidates are reconstructed in six modes:

$$\begin{array}{ll} J/\psi\, K^+ & J/\psi\, K^0_S \\ J/\psi (K^0_S\pi^+)^* & J/\psi (K^+\pi^-)^* \\ J/\psi (K^+\pi^0)^* & J/\psi (K^0_S\pi^0)^* \end{array}$$

where $J/\psi\rightarrow e^+e^-$ and $\mu^+\mu^-$ with $P_\ell > 0.8\,\mathrm{GeV}/c$. Dimuon candidates are required to be within $45\,\mathrm{MeV}/c^2$ of the known $J/\psi$ mass; the cut is asymmetric for dielectrons to account for radiation: $-150 < M_{ee} - M_{J/\psi} < 45\,\mathrm{MeV}/c^2$. To improve the $J/\psi$ momentum resolution, the dilepton pair is constrained in a kinematic fit to have the $J/\psi$ mass. To limit fake backgrounds the momentum of $\pi^0$ candidates is required to be greater than $200\,\mathrm{MeV}/c$ .

Because $B$ mesons are produced near threshold at the $\Upsilon(4S)$ resonance, their energy is equal to the beam energy. Therefore, CLEO requires the measured energy of $B$ candidates to be within $3\sigma$ of the beam energy, and in reconstructing the $B$-candidate mass, they use the beam energy rather than the measured energy to form the beam-constrained mass: $M_B^2 = E_{\text{Beam}}^2 + p^2(\psi K^{(*)})$. The cut on the energy difference $\Delta E$ largely excludes random backgrounds, and the $\Delta E$ sidebands provide a measure of such backgrounds. A more serious background source is "feed-across" in which a $B \to J/\psi\, K^*$ decay can appear as a different $J/\psi\, K^*$ decay mode if a soft pion is missed and a daughter from the decay of the $\overline{B}$ in the event is included in the reconstructed $B$ candidate. To reduce feed-across backgrounds, CLEO forms a probability from $\Delta E$, the measured $\pi^0$ mass, and $dE/dx$ and time-of-flight information for the hadron tracks. Candidate probabilities are required to be at least 1%, and if there are two candidates in the same mode, the one with the highest probability is selected.

The final significant background source is non-resonant $B \to J/\psi\, K\pi$ decays. No polarization is observed in $B \to J/\psi\, K\pi$ events above the $K^*$ peak. The contribution is determined to be 6.4% from extrapolation of a linear fit to the $K\pi$ mass distribution above the peak with a systematic uncertainty assigned to be the full value of this component.

The decay amplitudes are determined in an unbinned maximum-likelihood fit including contributions from:

- Branching ratios (*i.e.* normalization)
- A Gaussian signal function in $M_B$
- The angular distribution for $J/\psi\, K^*$ decays
- Non-resonant background vs. $M_B$ and decay angles
- Combinatorial background vs. $M_B$
- Feed-across backgrounds vs. $M_B$ and the decay angles.

The efficiency as a funtion of the decay angles used in the fit is determined from 120,000 Monte Carlo events per $K^*$ mode.

Figure 3 shows the result of the combined likelihood fit. The combined results for the amplitudes and phases are listed in Table 2. A significant relative phase between the amplitudes would indicate final-state interactions. However, the three amplitudes are consistent with being relatively real, providing no

Table 2: CLEO results for fractional amplitudes and relative phases in $B \to J/\psi\, K^*$ decays in the transversity basis.

| | |
|---|---|
| $\lvert A_0\rvert^2 \equiv\ ,\ _L/,$ | $0.52 \pm 0.07 \pm 0.04$ |
| $\lvert A_\perp\rvert^2 = \lvert P\rvert^2$ | $0.16 \pm 0.08 \pm 0.04$ |
| $\phi_\perp$ | $-0.11 \pm 0.46 \pm 0.03$ |
| $\phi_\parallel$ | $3.00 \pm 0.37 \pm 0.04$ |

evidence for a breakdown of factorization. In measuring $\mathcal{B}(B \to J/\psi\, K)$, the events are sufficiently clean that the statistical precision can be improved by relaxing the identification cuts on one lepton. The events are fit in $M_B$ only. The measured branching ratios for all four decay modes are listed in Table 1 along with the charge-averaged vector-to-pseudoscalar decay ratio.

## 4 CLEO Limits on $\mathcal{B}(B^0 \to D^{(*)+} D^{(*)-})$

$B^0 \to D^+ D^-$ is a pure $CP$ eigenstate. Decays to $D^{*+} D^-$, $D^+ D^{*-}$, and $D^{*+} D^{*-}$ are not; however, the dilution that would be incurred by treating them as pure in a measurement of $\sin 2\beta$ is predicted[12] to be small. The dominant decay process is the color-allowed $b \to c\bar{c}d$ transition which is Cabbibo suppressed. The branching ratios can thus be predicted from the corresponding Cabbibo-allowed ${D_s}^{(*)} D^{(*)}$ decay modes. The predictions are listed in the first line of Table 3. In a 3 fb$^{-1}$ data sample, CLEO has set limits on the branching ratios in these three decay modes[13] where the following charm modes are reconstructed:

$$\begin{array}{ll} D^{*+} \to D^0 \pi^+ & D^0 \to K^- \pi^+ \\ D^+ \to K^- \pi^+ \pi^+ & D^0 \to K^- \pi^+ \pi^0 \\ & D^0 \to K^- \pi^+ \pi^- \pi^+ \end{array}$$

The joint particle identification likelihood for the two kaons in a $B$ candidate is required to exceed 0.1, and the likelihood for each pion is required to exceed 0.05. A reconstruction $\chi^2$ is formed from the $D$ and $D^*$ mass pulls. The cut on this quantity varies from mode to mode. A kinematic fit for the beam-constrained mass is performed on candidate events with constraints from the charm-meson candidate masses and the decay vertices. The signal region is defined by a $\pm 2\sigma$ window in $\Delta E$ and $M_B$. The background is estimated from a larger sideband region in $\Delta E$-$m_B$ plane corrected for relative efficiency. Table 3 lists the number of events found in the signal region in each mode as well as the

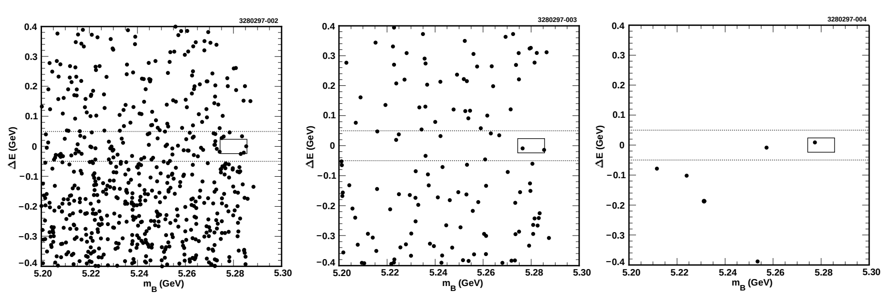


Figure 4: Scatter plots of $\Delta E$ vs. $m_B$ for CLEO $D^+ D^-$, $D^{*\pm} D^{\mp}$, and $D^{*+} D^{*-}$ candidates.

Table 3: Event yields and branching ratios for $B^0 \to D^{(*)+}D^{(*)-}$

| Mode | $D^+D^-$ | $D^{*\pm}D^{\mp}$ | $D^{*+}D^{*-}$ |
|---|---|---|---|
| Predicted Branching Ratio | 0.045% | 0.081% | 0.097% |
| Signal Events | 3 | 2 | 1 |
| Sideband Events | 539 | 117 | 4 |
| Predicted Background | $2.64 \pm 0.34$ | $0.64 \pm 0.10$ | $0.022 \pm 0.011$ |
| Efficiency (%) | 14.4 | 5.07 | 1.86 |
| 90% CL Branching Ratio Limit ($\times 10^{-3}$) | $< 1.3$ | $< 2.0$ | $< 2.5$ |

number of sideband events and the predicted background from the sidebands. The distribution of candidates in the $\Delta E$-$m_B$ plane is shown in Figure 4. For $B^0 \to D^{*+}D^{*-}$, the probability that the background fluctuates to the one event observed is 2% which if interpreted as a signal implies

$$\mathcal{B}(B^0 \to D^{*+}D^{*-}) = (5.3^{+7.1}_{-3.7} \pm 1.0) \times 10^{-4}.$$

## 5 Conclusions

The past few years have shown great strides in measurements of branching ratios and angular correlations in $B \to \psi K^{(*)}$ decays. From the measurements described above, it is possible to form the following average branching ratios:

$$\begin{aligned}
\mathcal{B}(B^0 \to J/\psi\, K^0) &= (0.91 \pm 0.13) \times 10^{-3} \\
\mathcal{B}(B^0 \to J/\psi\, K^{*0}) &= (1.34 \pm 0.20) \times 10^{-3} \\
\mathcal{B}(B^+ \to J/\psi\, K^+) &= (0.99 \pm 0.11) \times 10^{-3} \\
\mathcal{B}(B^+ \to J/\psi\, K^{*+}) &= (1.49 \pm 0.30) \times 10^{-3}.
\end{aligned}$$

Table 4 compares results on the polarization and vector-to-pseudoscalar ratio $R_{PV}$ to theoretical predictions. The model of Neubert *et al.* and Aleksan *et al.* show marginal agreement with the data. However, CLEO's measurement of the phases of the amplitides shows no evidence of final-state interactions and thus no evidence of a breakdown of the factorization hypothesis.

An estimate of the effectiveness of $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^0_S \pi^0$ compared to $J/\psi K^0_S$ for future measurements of $\sin 2\beta$ can be determined from the $P$-wave fraction in vector-vector decays and the relative yields in the CLEO analysis:

$$R_{fom} = \frac{\epsilon \cdot \mathcal{B}(B^0 \to J/\psi (K^0_S \pi^0)^*)}{\epsilon \cdot \mathcal{B}(B^0 \to J/\psi\, K^0_S)} (1 - 2|A_\perp|^2)^2 \simeq 0.06 \pm 0.03$$

Table 4: Comparison of experimental results with predictions of factorization models.

| | $\Gamma_L/\Gamma$ | $R_{PV}$ |
|---|---|---|
| CLEO | $0.52 \pm 0.08$ | $1.45 \pm 0.26$ |
| CDF | $0.65 \pm 0.11$ | $1.36 \pm 0.35$ |
| Expt. Average | $0.56 \pm 0.06$ | $1.42 \pm 0.21$ |
| BSW [2] | 0.57 | 4.2 |
| Neubert *et al.*[3] | 0.36 | 1.61 |
| Aleksan *et al.*[4] | 0.45 | 2.15 |
| Gourdin *et al.*[5] | $0.45^{+0.13}_{-0.17}$ | — |

Substantial improvement in efficiencies would be needed for the $J/\psi K^{*0}$ or $D^{(*)+}D^{(*)-}$ channel to have a meaningful contribution to future $CP$ asymmetry measurements. However, existing samples of $\sim 50$ $J/\psi\, K^0_S$ events in $3\,\mathrm{fb}^{-1}$ of $e^+e^-$ collisions and $\sim 200$ in $110\,\mathrm{pb}^{-1}$ of $\overline{p}p$ point to an exciting future.

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